An eye-adapted beamforming for axial B-scans free from crystalline lens aberration : In vitro and ex vivo results with a 20 MHz linear array

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An eye-adapted beamforming for axial B-scans free from crystalline lens aberration : *In vitro* and *ex vivo* results with a 20 MHz linear array

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Abstract - ***In ophtalmic ultrasonography, axial B-scans are seriously deteriorated owing to the presence of the crystalline lens. This strongly aberrating medium affects both spatial and contrast resolution and causes important distortions. To deal with this issue, an adapted beamforming (BF) has been developed and experimented with a 20 MHz linear array working with a custom US research scanner. The adapted BF computes focusing delays that compensate for crystalline phase aberration, including refraction effects. This BF was tested in vitro by imaging a wire phantom through an eye phantom consisting of a synthetic gelatin lens, shaped according to the unaccommodated state of an adult human crystalline lens, anatomically set up in an appropriate liquid (turpentine) to approach the in vivo velocity ratio. The synthetic lens shape corresponded to that of an adult human crystalline lens in unaccommodated state. Both image quality and fidelity from the adapted BF were assessed and compared with conventional delay-and-sum BF over the aberrating medium. Results showed 2-fold improvement of the lateral resolution, greater sensitivity and 90% reduction of the spatial error (from 758 μm to 76 μm) with adapted BF compared to conventional BF. Finally, promising first ex vivo axial B-scans of a human eye are presented.***

Index Terms - ***Biomedical sensors, Image Processing, Ultrasound.***

I. INTRODUCTION

In ophthalmic ultrasonography, axial B-scans are useful to depict essential intraocular structures (*e.g.* the crystalline lens, the macula, the papilla, the optic nerve) and to perform biometric measurement (*e.g.* axial length) in view of intraocular lens implantation.

However, axial B-scans have to face a significant obstacle: the crystalline lens which is known to be the major source of phase aberration in the eye as US propagate about 10% faster than in the surrounding intraocular medium. It acts as a divergent lens causing broadening, decrease in intensity and refraction (in the vicinity of the lens edges) of axial acoustical beams that finally impairs significantly both spatial and contrast resolution on axial B-scans and causes important distortions, especially on the ocular fundus. Thus, ophthalmologists recommend by passing the lens when possible.

To deal with this issue, an adapted BF has been developed and implemented on a custom US research scanner called the ECODERM and working with a 20 MHz linear array. The adapted BF lies on a ray tracing approach to compute focusing delays that take into account crystalline lens aberrations including refraction at the interface [1]. Interest of this adapted BF is investigated in relation with conventional delay-and-sum (DAS) BF throughout *in vitro* experiment conducted on an eye phantom mimicking the *in vivo* velocity ratio between the crystalline lens and the surrounding aqueous humor and vitreous. Finally, first axial B-scans conducted *ex vivo* on a human eye are presented.

II. MATERIALS AND METHODS

In vitro experiment consists in imaging a wire phantom with a linear array at 20 MHz, first in pure turpentine to establish the reference B-scan and then through a synthetic gelatin lens centered beyond the probe in an anatomical way. Raws RFs data obtained after linear scan in the presence of the aberrating media are then processed off-line (Matlab$^{©}$) according to DAS BF and adapted BF to obtain respectively a conventionnal B-scan and an adapted B-scan. Dynamic receive focusing was applied at each depth sampled ($f_s = 100$ MHz).

Turpentine and 15% gelatin offer low attenuation at 20 MHz and a velocity ratio that emphasizes the *in vivo* phase aberration induced by the crystalline lens.

Wire phantom is made of three wire ($\varnothing = 37.5\mu m$) rows spaced diagonnaly by 1 mm and horizontaly by 1.5 mm that cover regions of interest for ocular imaging.

Lateral resolution at -6 dB (Δl_{-6dB}) was quantified on every B-scan by measuring the FWHM of the point spread function (PSF) of 23 point targets (PT) from the wire phantom (numbered on Fig. 1(a)). Spatial fidelity of the B-scans over the aberrating media was evaluated by measuring the spatial error (Err_{total}) of each PSF in relation to the reference B-scan. Estimation of the sensitivity is provided by measuring the relative amplitude $G_{BF/Ref}$ between PSFs from B-scan through the synthetic lens with those from ref-

B-scan	$\widehat{\Delta l}_{-6dB}$ $[\mu m]$	$\widehat{Err_{total}}$ $[\mu m]$	$\widehat{G_{BF/Ref}}$ $[dB]$
Reference	251 ± 50	0	0
Uncorrected	776 ± 322	758 ± 129	-12.6 ± 4.6
CLAIFbC	352 ± 139	76 ± 71	-6 ± 4.7

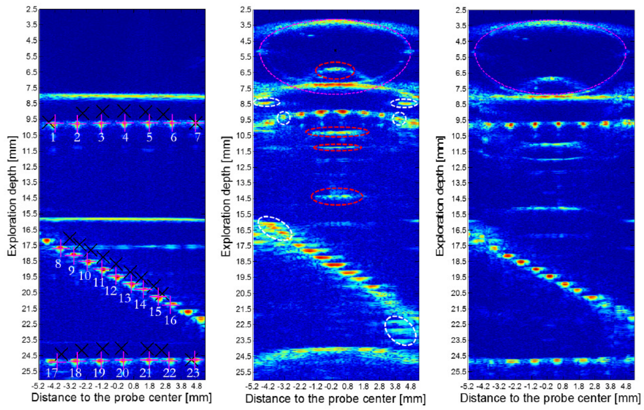
Table 1: Mean values $\pm SD$.

erence B-scan which is calculated as follows:

$$G_{BF/Ref}[n] = 20log_{10}\left(\frac{max(PSF_{BF}[n])}{max(PSF_{Ref}[n])}\right) \quad (1)$$

where BF refers either to DAS BF or to adapted BF, and n is the integer matching an analyzed PSF.

III. RESULTS



(a) Reference (b) Conventionnal BF (c) Adapted BF

Figure 1: *In vitro* B-scans of the wire phantom in pure turpentine (a) and through the synthetic lens with conventional BF (b) and adapted BF (c). PSF centers from matching PT in the conventional (black cross) and adapted (magenta cross) images has been superimposed on the reference. DR = 40 dB

Conventional BF (Fig. 1(b)) suffers from significant distortions and decrease in resolution compared to Reference 1(a). Adapted BF (Fig. 1) exhibits an obvious restauration of spatial fidelity, spatial resolution and sensitivity as one can appreciate for each PSF on Figs. 2, 3 and 4, respectively. Thus, adapted BF brought, in average (see Table 1), a reduction of spatial distortions of 90%, a two-fold improvement in lateral resolution (120%) and a sentivity twice as strong compared to convetionnal BF. Finally, $\widehat{\Delta l}_{-6dB}$ from the adapted BF is only 39% larger than the Reference.

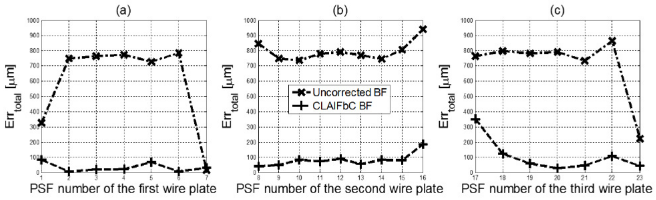


Figure 2: Spatial error compared to the Reference measured for each PSF on conventionnal (x-.) and adapted (+–) B-scans.

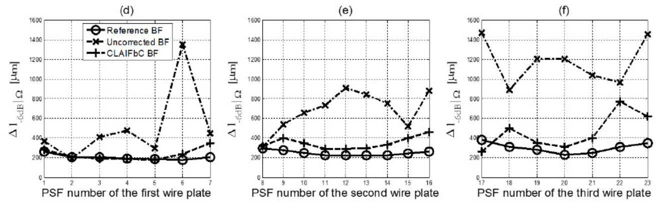


Figure 3: Lateral FWHM measured for each PSF on Reference (o-), conventionnal (x-.) and adapted (+–) B-scans.

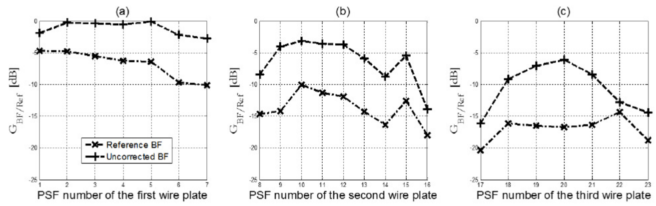


Figure 4: Sensitivity ($G_{BF/Ref}$ Eq. 1) measured for each PSF on conventionnal (x-.) and adapted (+–) B-scans.

IV. DISCUSSION-CONCLUSION

The crystalline lens detrimental effects on conventionnal axial B-scans with linear arrays has been demonstrated *in vitro*, as well as the efficiency of adapted BF in significantly reducing them. By acting directly in the BF stage, the proposed BF not only reduces the spatial distortions but also restores resolution and contrast. Such enhancements may provide improved visualization of the crystalline lens and the ocular fundus on axial B-scans as confirmed by first *ex vivo* results. Spatial fidelity delivered by adapted BF is also promising for B-mode biometry of the eye, especially for phakometry.

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